

Magnetic Solutions

Solving Inrush at the Source

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A simple approach based on original research attacks inrush currents at the source—the power transformer. The use of special core materials and transformer design/construction techniques overcomes the limitations of common inrush control solutions.

Often we try to find solutions to common power magnetics issues in engineering manuals. In the process, we encounter conflicting theories among publications with no definitive solutions offered. This is because power magnetics is largely considered a mature technology, and there's been little new theory development.

The issues of today aren't the same as in the past. We need higher efficiencies and increased power densities for "stuffability" into compact racks. Today's transformer designs solve problems that didn't exist in the recent past.

Transformers must work magnetically in closer proximity to other components and must dissipate thermally within smaller volumes with less forced air and reduced

surface area. Meanwhile, they must remain acoustically silent, endure the worst conditions of the dc-contaminated mains, and operate without interruption for the life of the product, including the shock of switch on. That's no ordinary piece of equipment. Despite the complexity of transformer requirements, there were too many questions for which we couldn't find answers. So, we developed a research program to discover causes and solutions to today's basic magnetic issues.

What is Inrush Current?

For the purposes of this discussion, inrush current is described as the magnitude of instantaneous current drawn by a line-frequency power transformer at the time the core is energized; it's of short duration, often milliseconds. Under a combination of certain conditions, inrush current can be measured at many times the rated load current. High inrush current is a time-dependent phenomenon caused by a coincidental set of circumstances that must occur simultaneously at the moment of switch on.

Inrush current is a problem, because it interferes with the operation of circuits as they have been designed to function. In a digital world, there is a zero tolerance for power interruptions. Period.

Some effects of high inrush include nuisance fuse or breaker interruptions, as well as arcing and failure of primary circuit components, such as switches. High inrush currents also necessitate oversizing of fuses or breakers, which complicates other aspects of approvals testing and may compromise protection on other vital components. Another side effect of high inrush is the injection of noise and distortion back into the mains.

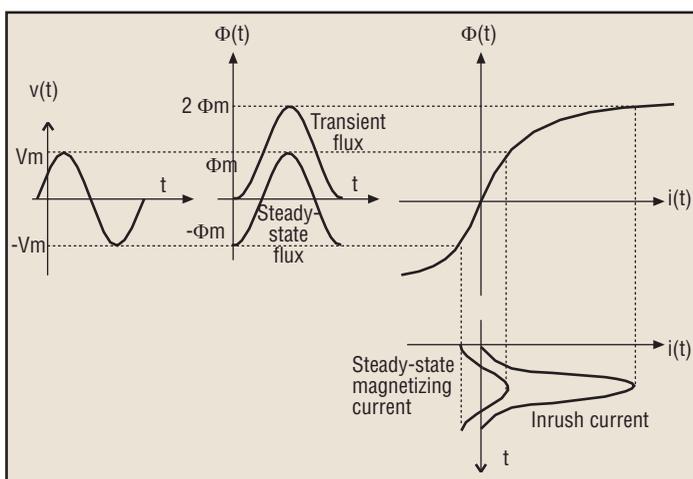


Fig. 1. Graphical description of the inrush current phenomenon.

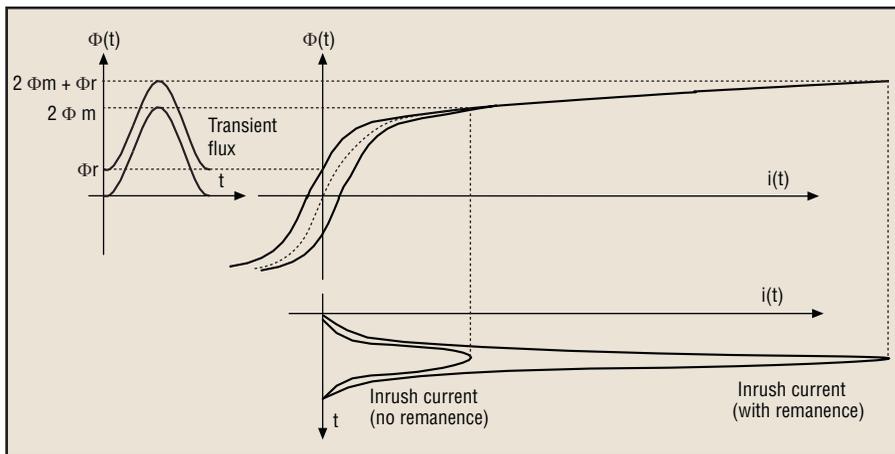


Fig. 2. Graphical description of inrush current phenomenon including remanence.

Power transformers for isolation and voltage step-up (or down) are among the most dated technologies still in use. Today's ac power grids evolved from the early days of the last century, when Tesla's generators faced off against Edison's dynamos to decide whether ac or dc power distribution would rule. Much has changed in a century; much has not. Materials have improved, manufacturability has increased and designs have moved

from engineer's charts to computer software. Nevertheless, power transformer theory and math have remained relatively unchanged since Tesla and Edison's time.

An excellent transformer reference source is the 1954 *Radiotron Designers Handbook*, published by RCA, which bears a remarkable magnetic similarity to today's reference books. The design approaches, rules-of-thumb and decision-making criteria

it offers could be considered as contemporary to the design approaches offered today. However, a quick comparison of electrical steels reveals the improvements in the last century. Although advanced for their day, the steels listed in the RCA 1954 *Radiotron Designers Handbook* can be characterized by as lossy, low in permeability, and as having soft hysteresis loops with long linear portions.

In the last few decades, steel companies worldwide have been driven to research new and better materials by industry demands for ever-higher power densities, lower costs, higher efficiencies and lower heat losses in a UL standards, MOUs and agency approved jungle. As a result of these research efforts, steel companies have successfully refined and improved the core materials—the key to transformer design.

Today's grain-oriented steels work with a fraction of the losses, at higher permeability, and they can be driven harder at elevated induction levels. But there are consequences. The mag-

	Standard Design	Low-inrush Design
Part reference number	8891	8108
Power (VA)	1000	1000
Inrush (A pk)	520	22
Size OD (mm)	164	170
HT (mm)	70	95
Frequency (Hz)	50 - 60	50 - 60
Weight (Kg)	7.5	9.8
Efficiency (%)	94.2	93.5
Regulation (%)	5.9	6.6
Temperature rise under normal load (°C)	54	48
Copper losses (W)	51	58
Core losses (W)	8	14
Cost comparison (reference only)	78	95
Requires external inrush circuit	Yes	No
Cost of extra components (reference only)	8	0
Other extra costs (reference only)	*5	0
Primary fuse rating (A)	** 12	8
Fuse type	Slow	Quick
Abnormal testing (A)	*** 22	15
*May need thermal switches to pass overload		
** Oversized fuse with slow reaction time to avoid nuisance interruptions		
***Medical 601 overload formula		

Table. Low-inrush transformer design example versus comparable standard transformer design.

netizing curve is no longer soft and round, because it has turned square and hard. However coincidental, the combination of high permeability and square loop comprise a major component of the formula for inrush.

Improved steels have enabled smaller, lighter and less costly transformers. Yet, those same improvements have created a generation of transformers that draw immense amounts of current at start up. Although it probably was not a problem in 1954, inrush current is definitely a problem today—one that concerns every primary circuit designer.

Physical Properties of Inrush

Transformer inrush currents are drawn by the high saturation of the iron core during the switching-in of the transformer. Fig. 1 illustrates a graphical description of the inrush current phenomenon, while Fig. 2 shows that remanence flux in the core

at the moment of switch on increases inrush current. Flux ϕ is generated as the results of applied voltage; it is then cross-plotted with ϕ -I characteristics to show the inrush current magnitude. This practice is shown for two cases: with and without resistance.

The driving force of the inrush currents is the voltage applied to the primary of the transformer. This voltage forces the flux to build up to a maximum theoretical value of double the steady-state flux plus remanence.

Therefore, the transformer is saturated and draws a large amount of current. Since the current is of short duration, no adverse effects occur to the transformer. However, the protective devices for overloads may falsely operate and disconnect the transformer.

The idealized behavior (ignoring resistances) of the inrush currents is governed by Faraday's Law:

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$$v(t) = \frac{d}{dt} \lambda(t) \quad (1)$$

Where $v(t)$ is the instantaneous voltage applied to the transformer primary and $\lambda(t)$ is the instantaneous flux linkage of the winding. Because the voltage is the driving force, the flux builds up according to:

$$\lambda(t) = \int_0^t v(t) dt \quad (2)$$

When we neglect the leakage flux, the following relationship is true:

$$\lambda(t) = N\phi(t) \quad (3)$$

where $\phi(t)$ is the total instantaneous flux in the core and N is the number of turns of the winding. Combining (2) and (3), we have

$$\phi(t) = \frac{1}{N} \int_0^t v(t) dt \quad (4)$$

If we assume that the voltage is sinusoidal

$$v(t) = V_{pk} \sin(\omega t + \varphi) \quad (5)$$

where V_{pk} is the magnitude of the sine wave.

Equation (4) results in:

$$\phi(t) = \frac{V_{pk}}{N\omega} [\cos\varphi - \cos(\omega t + \varphi)] + \phi(0) \quad (6)$$

Assuming that the remanence at $t = 0$ is $\phi(0) = \Phi_r$, the maximum flux that can be built in the core is when the closing angle is $\varphi = 0$ and $\omega t = \pi$. Under these conditions the maximum flux will be

$$\Phi_{\max} = 2 \frac{V_{pk}}{N\omega} + \Phi_r = 2\Phi_m + \Phi_r \quad (7)$$

UPS-Based Inrush Concerns

Considerable segments of today's power industry didn't exist two decades ago. Large markets have arisen out of the need for interruption-free power. The consequences of power outages, even local interruptions, can be devastating.

Much UPS technology relies on a primary plus a redundant, as well as "redundant" system, all sharing the same brain to ensure a constant power supply. Demand for backup systems to cut in can be instantaneous and without warning. At the moment of

switchover between systems, extremely high inrush currents can be generated as a result of timing and phase incongruities, dropped or missed pulses, double pulses, and other unforeseen conditions. The symptom is the same as inrush, and the transformer views it as inrush; thus, the same solutions are applicable.

As high inrush is the result of the

core momentarily residing in a state of saturation, it's cured when the core is resolved to normal operating flux levels. If uncontrolled, this may take several alterations. High inrush is commonly the result or combination of the following everyday line conditions: phase hopping, double pulsing, dc on the line (extremely common), transitory power outages (momentary

power failure, brownouts), reenergizing of the core in the same direction it was de-energized, and overvoltage on the line.

The line conditions described above are not typical of the power sent into the power grids by the utilities. The power is clean and undistorted when it's shipped. The problems are introduced by industry and households downstream from the power plants. Power line pollution is typically the result of load conditions, such as asymmetrical loads sending harmonics back into the power system.

Common Solutions

Several industry-accepted textbook solutions can resolve the problem of inrush. One is the introduction of an air gap into the magnetic circuit, which can lower the permeability and round out the shape of the hysteresis loop. The introduction of an air gap into the magnetic path transforms the magnetizing curve to an ideal shape. This system is old, but if done in a repeatable controlled manner, it's definitely capable of controlling inrush.

However, the shortcomings of core gapping are cost and major performance degradation. The gapping process is tedious and expensive. Cores need annealing as usual, and then treatment to bond the laminations, cutting, polishing, gapping, assembling and testing. The treatment and cutting process adds great stress to the steel. It may not be feasible to have the cut cores to re-relieve these additional stresses in an extra stage of annealing, because the varnishes and lamination bonding agents will vaporize and contaminate the furnace.

Producing gapped cores is expensive and labor-intensive. Moreover, core gapping may be difficult to repeat accurately given large manufacturing tolerances. Also, gapped cores lose many of the benefits of standard or toroidal cores, increase losses and increase exciting currents exponentially (typically 20 times the magnitude of gapless construction). What's more, they make it virtually impos-

sible to contain the enormous stray fields caused by the fringing of magnetic field lines close to the gap. These stray fields will affect all components in close proximity to the transformer, increasing the need for physical space or complicating shielding solutions.

Ultimately, core gapping causes the transformer to have lower efficiency, larger size, more weight and greater cost. This approach also makes it more difficult to keep laminations from rattling as a result of movements of the core halves. In some cases, it becomes difficult to keep the transformer acoustically quiet. So while gapped cores offer an effective solution to inrush, they create issues in other parts of the product.

Another form of inrush control relies on external components to contain the overload issue at predetermined manageable levels. However, these components deteriorate with time, temperature and mechanical stress, and can fail at any time. Additionally, external devices in the primary circuit add expense and complicate the required safety approvals, such as CSA and UL approvals. Moreover, they don't address the source of the problem.

Dependence on external components may not represent the best long-term choice to achieve the goal of perpetual power product performance for several reasons. They increase the parts count on the bill of materials, increase assembly time and add to the list of things that must be designed. Meanwhile, external components increase the

number of things that break down and increase stress for primary circuit devices. For example, this may cause the difference between a 15-A device or a 50-A IEC switch for the purpose of surviving inrush. External components for inrush control also may add series impedance to the primary circuit.

External Components. External components such as resistors, relays, timers and inrush thermistors in the primary circuit can be used to attenuate inrush. The theory is to add impedance to the primary during the incident of switch on and dissipate the energy through passive components. At a predetermined moment, a relay relays or an actuator actuates, and the short-lived line impedance is shunted out of the picture.

There are electrical circumstances beyond the capabilities of the external components under which the system may not function. A time constant is required to reset these components, and they may not perform well at the repetition rates encountered in the real world. Consequently, the external components may fail to react to consecutive or repeated power glitches. This system can sometimes be ineffective under conditions of low line or in situations of momentary power outages.

Inrush Thermistors. These devices aren't friendly to the medical industry because of the long recovery time and excessive temperatures during normal operating conditions. Inrush thermistors, which can be described as cur-

rent-sensitive resistors, are installed in series with the primary circuit. Their standard quiescent cold condition offers high resistance as a means to reduce inrush. As current starts to flow, the resistance drops to a small value that would have a minimal affect on the stabilized circuit. As a rule, they run hot, and a time period is required to recover to normal state.

If this concept is to operate flawlessly, there must be an inherent assumption that all circuits are energized only in a cold condition. Of course, circuits also can be energized in a hot condition, in which case the thermistor hasn't returned to the low-impedance state of equilibrium, and may not operate in a functional method to control inrush. A quickly repeating power line drop can result in the breakers opening.

Soft-Start Circuitry. Rather than offer impedance to the line at startup, soft-start circuitry places about half the rated voltage across the input at the moment of startup. Typically, this system is used in noncritical applications, and isn't employed in medical or data backup applications.

Beyond these common solutions to inrush control, many inrush fixes are implemented randomly and not necessarily on a scientific basis. One example is low-flux transformer design. Another is the use of high-resistance transformer windings.

Transformer-Based Solution

The ideal solution would attack inrush at the source and not rely on external components. It would not attenuate the inrush, it would eliminate it. Looking into the mains from the primary winding, the ideal solution for inrush would operate like a gapped core, but without the gap.

The ideal transformer solution for inrush would reduce or eliminate reliance on external parts or circuits. At the same time, it wouldn't compromise transformer quality, maintaining low stray fields, good thermal characteristics and high electrical efficiency. The ideal solution also would use common materials available from several sources and enable high manufacturability and repeatability on existing production machinery.

The challenge is to develop a transformer that operates magnetically on a similar curve to a gapped core yet is not gapped. Our solution initiated with an evaluation of the issues contributing to inrush, which needed to be quantified. We needed to gain a knowledge of mains conditions on a global scale that were considered as normal or adverse for such items as high and low lines, distortion, dc on the mains, transients and other conditions.

Furthermore, it was necessary to evaluate electrical steels far beyond the performance guarantees offered in the ASTM manuals. Many engineers have learned the material specs are just the starting point and can be considered as "typical performance." Often lab testing is necessary to indicate how hard the material can be pushed, or what it can do in the real world.

One of the major components in the quality of electri-

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cal steel is the processing. Through the slitting and annealing process, stresses manifest themselves in the form of losses introduced into the material. These stresses are somewhat relieved in the final anneal. However, the amount of stresses introduced to a core and the skill to remove them are highly based on the handling, slitting, core assembly, anneal cycle and cooling rate, and vary among different suppliers. Therefore, process control and consistency is vital to ensure dependable steel.

It was apparent the performance points offered by the mills were not well suited for our purposes. Steel that was at the high end of the tolerances wasn't good quality and couldn't be considered a premium. If we were to control inrush, then a prerequisite would be to ensure material with a consistent permeability from week to week, master coil to master coil, and from production run to production run. Therefore, it was necessary to rewrite steel specs in a manner that would offer a constant material, but not so much as to make it difficult to source, nor raise the price, nor complicate the processing.

Next, we looked at the theory and physics. We derived some mathematical solutions to identify and disentangle the flux components and determine their contribution to B_m . Then we assigned variables for line conditions, steel characteristics, tolerances and contributions of windings (that is, the primary resistance), and constructed a model of what we needed the core to do to remain linear and thus not saturate.

The variables were now in place, and we determined that a grade of steel that would solve all of the above conditions and fix inrush wasn't available commercially. It's not easy to get steel companies to change anything, so we would need to change something.

Our work was with toroids, although the theory applies to any core geometry. We knew the characteristics of steel grades were greatly altered through processing (as previously described). To ensure consistency of supply, we started with common steel grades in ample supply to determine the effects of modifications to customary manufacturing and treatment processes. We determined that small changes in process could vary the core characteristics greatly.

After some research and experimentation, we developed a new technology in which the core's curve emulated a gapped core without the gap. The magnetizing curve was round and smooth in shape, including a long linear portion, with a rounded hysteresis loop. Consequently, transformers built using such a core will tolerate severe overload while maintaining linearity.

We could control the tolerances and processes to the point where the material was consistent and repeatable, readily available and didn't increase costs. The basis of the development is the application of new magnetic core material derived from standard steel, with high manufacturability and an easily repeatable, guaranteed characteristic. This provides an excellent remedy to solve inrush current.

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The proprietary gapless technology has been dubbed "Imin," and several thousand Imin transformers have been operating successfully worldwide for the last four years. The solution is absolute, and since its introduction and pilot run, no occurrences of issues related to inrush have been reported.

The newly developed hysteresis loop emulates a gapped core but eliminates the problems associated with it.

We solved the inrush current problem by using special core materials and design/construction techniques. Our solution doesn't require external components; however, the toroidal transformers built using our technology can be bulky and more expensive than conventional toroids. But with our technology, the magnitude of the inrush currents has become another transformer design specification to meet rather than a problem.

As with any technology, there are trades and balances, and transformer-based inrush control is no exception. However, the system has to be evaluated as a complete solution, and overall, this approach solves more issues than it creates.

In general terms, the side effects of the system include reduced power densities or, conversely, increased size and weight. Stray magnetics tend to increase, so if magnetics are an issue, they need to be addressed at the time of design. In addition, transformer efficiency and regulation may

drop, and the transformer's temperature rise may increase. Nevertheless, all of these potential problems can be solved at the time of design.

Of course, control of inrush in a product must be part of an overall solution, and to be viable must offer an effective overall solution to the entire product. Presently, the largest UPS companies in the world have selected this technology to power their back-up products in the 2.5-kVA to 10-kVA power range, with larger sizes in the works. Currently, there are more than 10,000 installations of Imin technology, which have been supplied in the last three years, and are operating successfully all over the world.

An evaluation of the entire primary circuit should be undertaken to determine the overall cost and value of the transformer based solution to inrush in a given application. Although the transformer when viewed in isolation is larger, heavier and higher cost, the solution offered is typically cheaper to design, manufacture, warranty and service. The example presented in the table is a rough comparison of a 1-kVA system. As the power increases, so do the benefits, and the cost differential between the inrush control technology and standard technology is reduced.

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